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INTEGRATION OF 100% HEAT PUMPS AND ELECTRIC VEHICLES IN THE LOW VOLTAGE DISTRIBUTION NETWORK: A DANISH CASE STUDY

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ABSTRACT

The existing electricity infrastructure may to a great extent limit a high penetration of micro-sized Distributed Energy Rescores (DERs), due to physical bottlenecks, e.g. load capacities of cables and transformers and voltage limitations. In this study, integration impacts of heat pumps (HPs) and electric vehicles (EVs) at 100% penetration level on a representative urban residential low voltage (LV) distribution network of Denmark are investigated by performing a steady-state load flow analysis. Three DERs integration strategies, namely uncontrolled operation, half-direct controlled operation (the direct control only applies on HPs) and full-direct controlled operation (the direct control applies on both EVs and HPs), are modelled and simulated. The quantitative analysis proves that, by implementing a simple merit of order control strategy to manage congestions, having 100% integration of DER in the provided LV network is feasible.

Keywords: congestion management, electric vehicle, heat pump, low voltage distribution network, merit of order

INTRODUCTION

To understand the potential impacts and bottlenecks of integrating large-scale micro-sized distributed energy resources (DERs) into an electricity infrastructure under different integration strategies requires in-depth analyses. Such analyses normally follow a generic analysis framework as in Fig. 1, which consider three fundamental blocks as inputs.

- Modelling of network and DERs
- Integration strategies
- Evaluation criteria

In addition, proper analysis principles are selected beforehand to ensure the consistency and continuity of the analysis. For instance, a steady state load flow analysis with DERs' models at moderate granularity levels is usually considered as a primary analysis tool for planning and operation studies in relation to DERs integration.

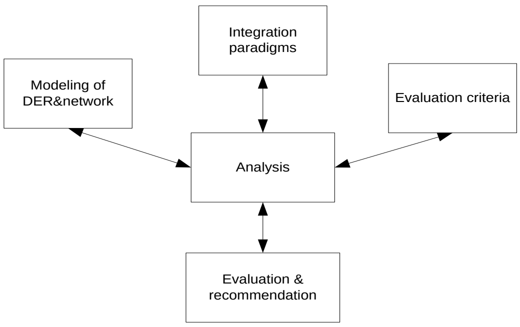

Figure 1: Schematic framework for DERs integration analysis

Heat pumps (HPs) and electric vehicles (EVs), as two promising green alternatives, have attracted much attention. A number of studies have been performed to analyze the potential impacts of having large-scale HPs or EVs in different networks.

Earlier studies [1]-[2] have demonstrated EVs' integration impacts on rural and urban networks using practical distribution models, i.e. Bornholm and Gothenburg respectively. Congestion issues have been perceived at 10kV level with 10% EV penetration for the rural network of the Danish island Bornholm; while for the urban network of Gothenburg, 100% EV penetration will overload one cable in the 0.4kV network and will result in a large number of overloading in the 10KV network. While in [3], an overview of various impacts associated with EV integration is presented. In case of HPs integration analysis, [4] uses fractal algorithm to create generic large-scale networks to resemble the real UK low voltage (LV) distribution networks. Results have shown that having 30% HPs in urban and rural LV networks will lead to 30% and 50% increase of the peak loads respectively, indicating severe congestions problems.

Realizing the potential physical bottlenecks in the distribution networks, e.g. load capacities of cables and transformers and voltage limitations, an enormous effort has also been made by researchers to manage congestions through better control solutions applied to DERs. The studies performed in [5]-[6] introduces centralized optimization technique to alleviate grid congestion at scheduling phases; while in [7]-[8] decentralized control approaches with price signals are proposed to manage EVs and HPs respectively for congestion alleviation.

In this study 100% integration impacts of HPs and EVs on a Danish representative urban residential LV distribution network are investigated by performing a steady-state load flow analysis over an annual period in DIgSILENT Power Factory. The term "100%" is defined as a circumstance where each household has an EV and a HP system.

Three integration strategies are formulated in this paper to analyse the impacts of 100% integration of HPs and EVs in a given network, namely

- **Uncontrolled operation**, i.e. the charging of EVs overnight follows the end users' instant demand and the operation of HP systems is heat-driven
- **Half-direct controlled operation**, i.e. the HP systems are directly controlled by the network operators in case of grid congestions. The EVs are in this case under uncontrolled operation.
- **Full-direct controlled operation**, i.e. the HP systems and the EVs are co-ordinately controlled by the network operators in case of grid congestions.

The rest of this paper is organized as follows: In the following section, the simulated urban residential LV distribution network of Denmark is described, together with the operational criteria. Afterwards, models for EVs and HP systems under different integration strategies are illustrated. A case study is presented and analysed subsequently, while conclusion is drawn in the end.

LOW VOLTAGE DISTRIBUTION NETWORK

The Danish LV-distribution network operation policy mostly follows the European Network Regulation Standard EN50160 [9], with respect to the voltage characteristics. According to the Danish REKOMMANDATION 16, the nominal supply voltage is 230 V between phases and neutral, and 400V from phase to phase. The limits for both voltage drop and voltage increase measured as a 10-minute average must be within the range of +/-10% of nominal supply voltage.

In this study, the maximum voltage tolerance is set to be in the range of +/-5% of nominal supply voltage as to take into account the possible imbalance between the phases. This is due to the fact that HP systems and EVs are normally installed on one phase only and can lead to uneven distribution between the three phases.

The selected urban LV network of Denmark is modelled in DIgSILENT Power Factory. As depicted in Fig.2, it consists of four different types of cables with a total length of 776 meters. The LV feeder is fed by a 10/0.4KV transformer and supplies 42 residential customers. In Table 1 (see last page), a detailed description of connections between the households and the LV cabinets is given.

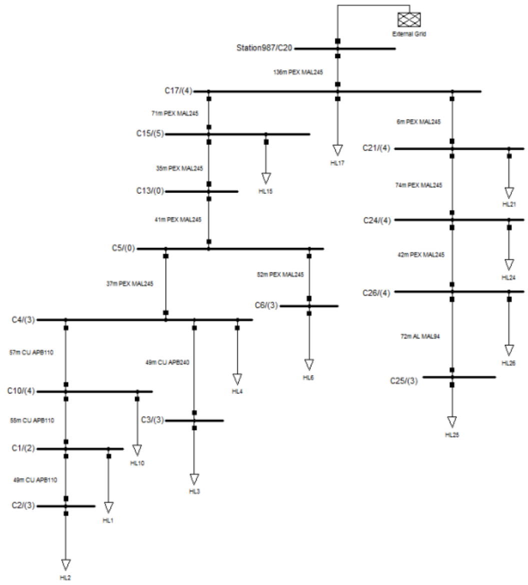

Figure 2: The simulated urban area LV network

SIMULATION MODELS FOR DERS

EV model

An electrical charging profile of an EV is highly dependent on the user's driving pattern and the characteristics of the EV battery. In this study, both factors are included in the EV model.

The driving pattern is in this study based on the assumption that the EVs are to replace the gasoline cars without affecting the users' driving experience. Practical Danish driving pattern for gasoline cars, as depicted in Fig.3 (see last page), is therefore applied to estimate the charging pattern of EVs and the battery energy required to meet the individual users' driving needs[10]-[11]. The energy demand for the EV is assumed to be 11kWh/100km.

Due to its high density on power and energy, the Lithium-ion battery technology has been commonly adopted by the automotive industry for vehicle electrification. A 28kWh Lithium-ion battery is modeled based on the approach presented in [11] to represent the battery of a medium size family car in Denmark. The state-of-charge (SOC) range is set to between 10% and 90%, and the efficiency of charging and discharging are both assumed as 90%.

Apart from the above mentioned assumptions, the followings are made in modeling the uncontrolled charging of EVs overnight:

- The EVs are charged overnight at home with a constant single phase charging power of 2.3kW as long as they are not used for driving
- The night charging period lasts from the first stop after 5pm (arriving home) until the first driving after 8am (leaving home)
- Within the charging period, EV charging is terminated when the maximum SOC is reached
- The power factor of EV chargers is assumed to be 0.95
- The EVs deployed in the urban network are identical and equally distributed among three phases

HP system model

The empirical model a HP system (including an air-source HP, an auxiliary electric heating element and a thermal storage tank) is illustrated in Fig. 4. The model is designed by the Danish engineering consulting company Balslev within a category for smart grid technologies (SGT).

This model takes outdoor temperature, building data and technical specification of HP as inputs, and produces the electrical load profile of a residential HP system. Basically, the residential heating demand for both space heating and water heating $E_{heating,T+WW}$ is supplied by the HP via the thermal storage; in other words, the on/off of the HP is controlled by the temperature of storage tank T_{Tank} . However, when the coefficient of performance (COP) of HP is less than 1, the heating element will be turned on as an alternative of the HP. In case of high heating demand, both HP and heating element need to be in operation, implied by T_{HP} and $T_{heating\ el.}$ as the operation periods for HP and heating elements respectively, to assure the desired indoor temperature. More details about the model with numerical examples are available in [12].

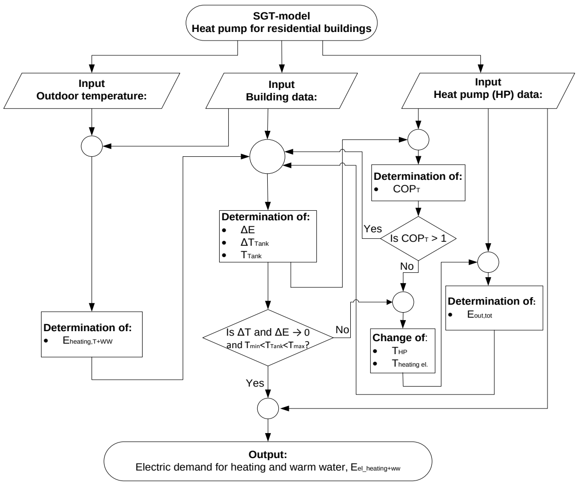

Figure 4: Schematic overview of the HP system model

In this study, the following assumptions are made to further clarify the HP system model:

- The electric motor of HP has a nominal power of 3.1kW with a power factor of 0.95
- The resistive heating element in the HP system is 3 kW
- The water tank has a size of 2 m^3 and an operational temperature range between T_{min} 45°C and T_{max} 65°C
- Desired indoor temperature is assumed to be constant at 20°C
- 8 types of houses which differ in the thermal insulation are randomly assigned to the 42 households to generate different heating demand
- All HP systems deployed in the urban network are distributed equally among the three phases
- Practical outdoor temperature obtained from [12] is utilized

INTEGRATION STRATEGIES

Uncontrolled operation

As mentioned in the introduction, the operation of the EVs and HPs follows the instant demands of the users.

Direct controlled operation

When the network is congested in terms of voltage limitations and line capacities, etc., one possibility of alleviating the congestions is to allow the network operators to directly control the DERs following certain pre-defined principles, e.g. merit of order.

Taking the directly controlled HPs as an example, as illustrated in Fig. 5, water temperature of the heat tanks of all HP systems are collected and sorted by network operators continuously. When congestion occurs at time slot *i*, HP systems with the highest tank temperature will be disconnected. The action of disconnecting the HP systems will continue until the congestion is alleviated; while in the next time slot, the stopped HP systems will be turned on again if they satisfy the HP systems' "on" criteria. In this study, this approach of using HP systems alone for congestion management is named "**half-direct controlled operation**".

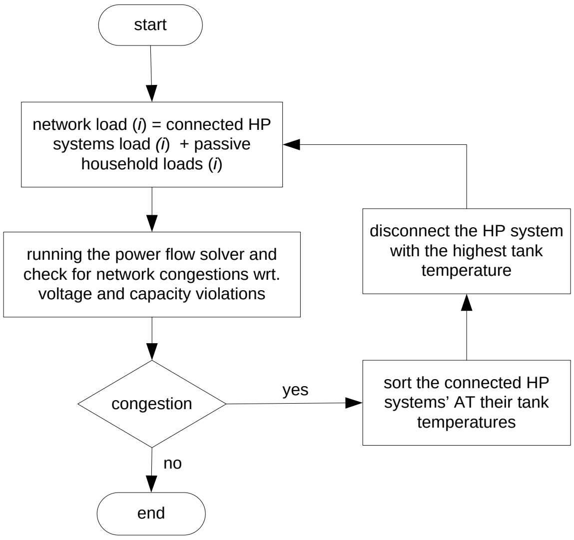

Figure 5: The Flow Chart of Direct Controlled Mode of a HP system

This principle can also be applied to a circumstance where HP systems and EVs are controlled both by the network operators, or namely "**full-direct controlled operation**". In such case, the merit order of DERs can be sorted according to the time left to reach the maximum energy level of the storages, i.e. batteries and water tanks, expressed in τ_{left}. This measurable index τ_{left} to a great extent reflects the DERs users' satisfactory level. In case of congestion, the DER that needs the shortest time to reach a full charge of its storage will therefore be disconnected first.

SIMULATION RESULTS

In this section, the three integration strategies of the DERs in the chosen LV network at 100% penetration level are simulated with the time resolution of 1 hour. Further, the performance of three strategies over a 1-year period is analysed.

Uncontrolled operation

Fig.6 illustrates the outdoor temperature in 2 consecutive winter days, which is applied to the simulation study. Temperature in the 1st day is relatively flat until 3pm when it starts to decrease fast. The lowest temperature within the 2 days is around -5.5°C, taking place in the midnight of the 2nd day.

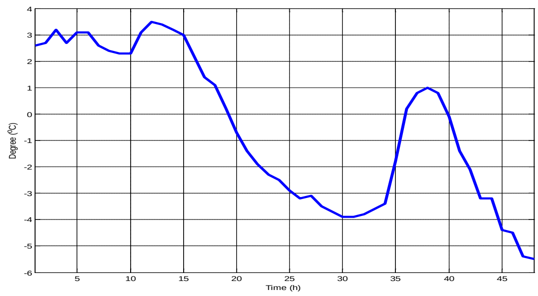

Figure 6: Outdoor temperature in 2 consecutive winter days

The aggregated electrical load profiles of HP systems, EVs and household loads in the simulated LV network are illustrated respectively in Fig. 7 in per unit (pu) values. The aggregated household loads follow a general pattern wherein the daily peaks are around 6pm. Peak loads of the EVs occur in the same moments, as users start to charge their EVs immediately after they arrive home. The aggregated load profile of HP systems does not have a clear pattern due to variations of both household types and initial values of the water tank temperatures at the beginning of the simulation; however it shows that the total electrical consumption of HP systems is relatively large when the outdoor temperature appears to be low. Overall, the maximum capacity of the top feeder, as depicted by the red line, is exceeded twice at 7pm in the 1st day and 6pm in the 2nd day.

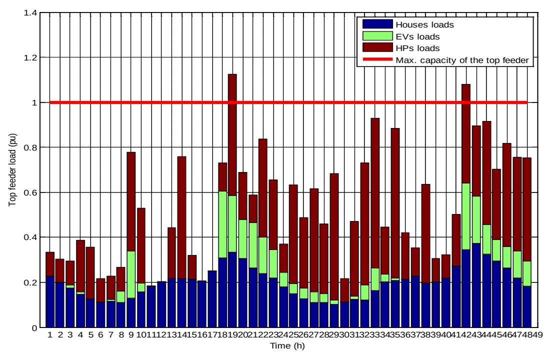

Figure 7: Load profile of the LV network without congestion management

Besides exceeding the capacities of distribution lines, the voltage settings of this network are also violated in several high load moments. This is well illustrated in Fig. 8, wherein the lowest terminal voltage value of the entire network of each hour is plotted.

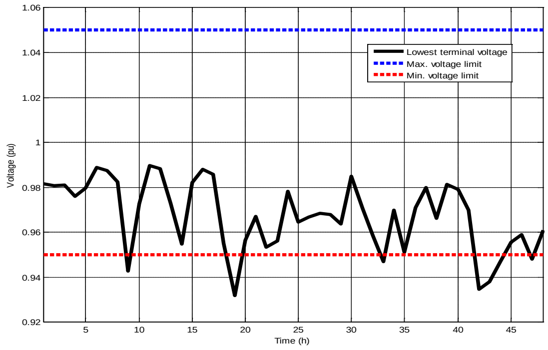

Figure 8: Lowest terminal voltage values in the LV network without congestion management

Half-direct controlled operation

In the case of having only HP systems for congestion management, the simulated load profile and voltage profile of the given LV network are presented in Fig. 9 and Fig. 10 respectively. It shows that by disconnecting a number of HP systems in the congestion moments, both voltage and line capacity violations observed in the previous simulation case are eliminated.

Disconnecting a HP system when its T_{Tank} is close to T_{min} may require the HP system to be immediately turned on in the next operational time slot, and will further cause or exacerbate the congestion problems in several hours in a row. In Fig. 9, this phenomenon can be found for several times, such as the period from hour 9 to 10 and from hour 19 to 20. To shift the load to appropriate periods, the direct controlled approach will therefore be executed repeatedly until the congestions are eliminated.

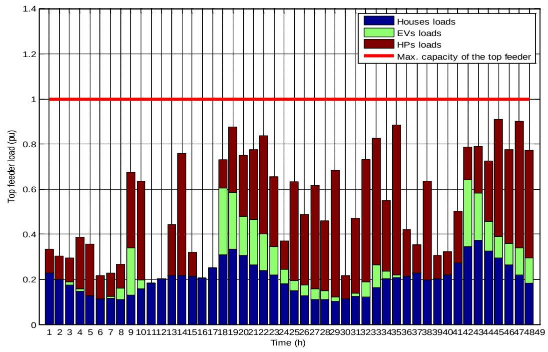

Figure 9: Load profile of the LV network under half-direct controlled operation

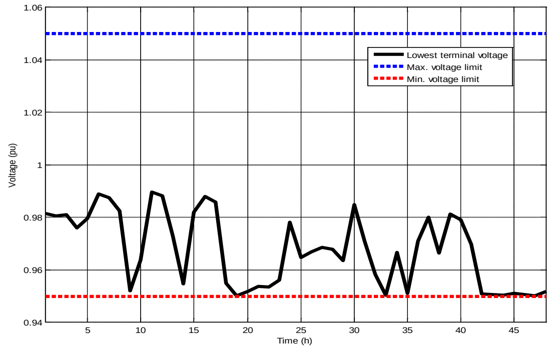

Figure 10: Lowest voltage values in the LV network under half-direct controlled operation

An illustrative example for the control process over HP systems in the first congestion moment (i.e. hour 9) is given in Fig. 11, where 5 HP systems are disconnected consecutively in order to ensure the lowest terminal voltage value of the network (in green) is within the pre-defined operational boundary. The top feeder load (in red), i.e. loading of the network, also decreases associated with voltage increase.

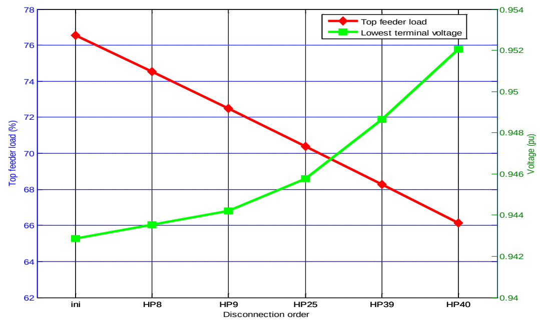

Figure 11: Congestion management with half-direct controlled operation in hour 9

Full-direct controlled operation

For full-direct controlled operation, the simulated load profile and voltage profile of the given LV network are presented in Fig. 12 and Fig. 13 respectively. Compared with the half-direct controlled operation, the resulted voltage profile is almost the same except for a small increase of value of the lowest terminal voltage in hour 21. Due to the congestion management, the total load of EVs experiences a dramatic change in hour 9, 10, 19, 42 and 48, etc., while the load of HP systems closely resembles its load curve under uncontrolled operation since the value of τ_{left} for water tanks is normally larger than the value of τ_{left} of most EVs.

Similar to disconnecting the HP systems, disconnecting the EVs may also lead to a recurring phenomenon where the congestion occurs consecutively. However, it is worthwhile to note that disconnecting EVs may lead to more consecutive congestion events than the case of disconnecting HP systems. This is because a disconnected EV is immediately reconnected for charging as long as its battery is not fully charged, while for a disconnected HP system, it is not turned on again until its T_{Tank} value is less or equal to T_{min}.

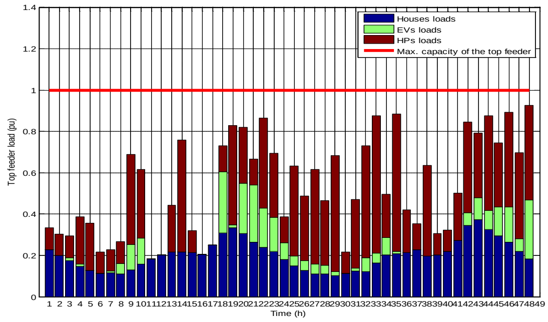

Figure 12: Load profile of the LV network under full-direct controlled operation

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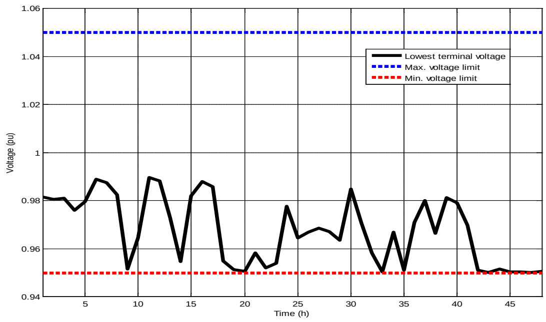

Figure 13: Lowest voltage values in the LV network under full-direct controlled operation

In Fig. 14, the control process in hour 9 under full-direct controlled operation is illustrated. Compared with half-direct controlled operation, 9 EVs have to be disconnected in order to bring to the voltage above 0.95 pu. Because the SOC of some EVs are already close to their maximum limits and the disconnection leads to variations of system losses, the loading reduction (in red) is in a near-linear shape as shown in Fig. 11.

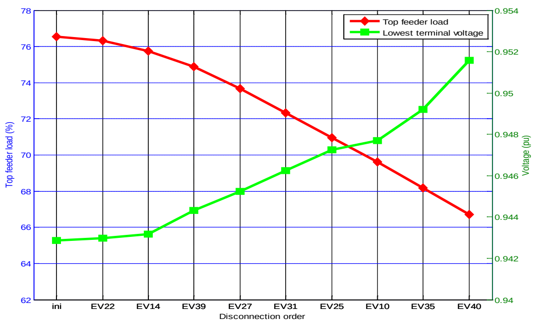

Figure 14: Congestion management with full-direct controlled operation in hour 9

Annual performance

The annual performance of three integration strategies is summarized in Table 2, while the cost of electricity is calculated based on the hourly electricity wholesale price for east Denmark of 2011 published by Nordpool Spot [14]

It can be found that both half-direct control and full-direct control manage the congestions very well. The resulted average electricity consumption per household (including EV, HP, passive load and network losses) and the corresponding annual electricity cost are found very close among the three integration strategies.

Table 2: Summer of annual performance

	Integration Strategies		
	Un-control	***Half-direct***	***Full-direct***
min. voltage (pu)	0.91	0.95	0.95
max. loading (%)	134	91.49	91.63
no. of voltage violation	205	0	0
no. of capacity violation	33	0	0
el con. per household (kWh)	9415	9405	9408
cost per household (DKK*)	3660	3652	3651

*(1 Euro= 7.46 DKK)

CONCLUSION

In this study, the feasibility of 100% penetration of DERs, i.e. EVs and HPs, in a Danish urban LV distribution network is investigated through a state-state load flow analysis. Study shows that, by having simple directly controlled congestion management algorithms, having 100% DERs is proved to be feasible for the given network. Although the full-direct control operation gives the network operators more flexibility of DERs management than the half-direct control operation, according to the annual performance, the suggested two congestion management approaches have almost the same economic performance and none of them brings in inconveniences to the users' experience. One possible reason could be the provided urban LV distribution network has a relatively large capacity to accommodate a high share of DERs and therefore the frequency of congestion is not high. Another reason could be due to the selection of outdoor temperature used in the simulation, which can noticeably affect the load of HP systems.

In further studies, user-defined cost functions for being disconnected/controlled can be taken into account in order to estimate the users' involvement in and their impacts on the distribution system operation in a more precise manner.

ACKNOWLEDGMENT

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Table 1: LV cabinets vs. households .

LV cabinets/ (no. of connected households)	C25 /(3)	C26 /(4)	C24 /(4)	C21 /(4)	C17 /(4)	C15 /(5)
Connected household no.	HL 1-3	HL 4-7	HL 8-11	HL 12-15	HL 16-19	HL 20-24
LV cabinets/ (no. of connected households)	C3 /(3)	C6 /(3)	C4 /(3)	C10 /(4)	C1 /(2)	C2 /(3)
Connected household no.	HL 25-27	HL 28-30	HL 31-33	HL 34-37	HL 38-39	HL 40-42

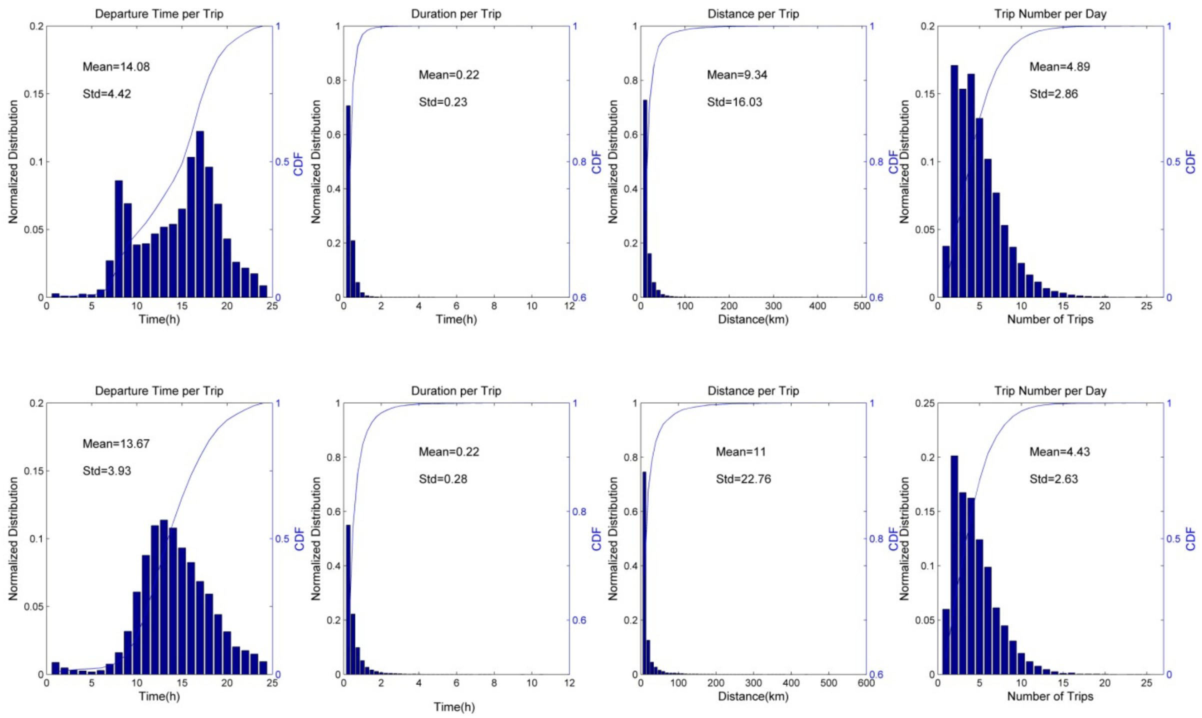

Figure 3: Statistical driving pattern derived from the Danish AKTA GPS-data (weekdays 1st row, weekends 2nd row)